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Full Length Research Paper

Permeability characteristics of pumice-bentonite mixtures in comparison with sand-bentonite mixtures

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Environmental pollution is a significant concern around the landfill sites, waste repositories and other similar wastewater storage and treatment basin and ponds. Pumice is an abundant natural material in Kayseri, Turkey and therefore, permeability characteristics of pumice-bentonite mixtures were investigated in comparison with commonly used sand-bentonite mixtures. Four different bentonite contents (15, 20, 25 and 30%) and three grain size ranges (2.00 to 1.00; 1.00 to 0.50; 0.50 to 0.25 mm) of pumice and sand were used to determine the hydraulic conductivity of mixtures. Since it takes long time to determine the hydraulic conductivity of fine grained mixtures, empirical equations were developed between permeability and easily-determined geotechnical characteristics such as dry unit weight, moisture content, and swell potential of such mixtures. Pumice-based mixtures yielded identical permeability values for the same bentonite contents and size ranges. Overall evaluation of regression equations with regard to mean absolute error (MAE) and regression coefficients showed that while dry unit weight yielded the least MAE and the highest R^2 values for pumice-based mixtures, swelling potential yielded the best estimations for sand-based mixtures. Bentonite content of ≥ 30% is recommended for both pumice and sand-based mixtures with grain sizes between 2.00 and 0.50 mm and ≥25% for mixtures with grain sizes less than 0.50 mm.

Key words: Pumice, bentonite, mixtures, permeability.

INTRODUCTION

Environmental pollution is a significant concern around the landfill sites, waste repositories and other similar wastewater storage and treatment basin and ponds. Pollution due to leakages from such structures is a well-known and widespread problem. Liner systems or barriers are commonly used to prevent or limit the seepages from these sites. Various liner or barrier materials such as plastic membranes, geo-textiles, bentonite, compacted clay, cement stabilized products, several different waste products and mixtures are used to prevent leakages. Such liners require careful design and consideration of variations in hydraulic conductivity, composition, water content, compaction and swelling characteristics (Sällfors and Öberg-Högsta, 2002).

Landfills are usually lined with low permeability materials such as geo-membranes and mineral layers to contain the leachate produced by the waste. Bentonite enhanced sand liners are of growing interests because they are less susceptible to frost damage and undergoes less shrinkage on drying than compacted clay liners (Kraus et al., 1997). Compacted expansive soils and clays are often considered as useful materials for construction of the engineered barrier to be placed between waste and the host rock (Akgün et al., 2006). Compacted bentonite and sand-bentonite mixtures are attracting greater attention as buffer and backfill materials because they offer impermeability and swelling properties. Therefore, hydraulic conductivities of compacted mixtures with regard to dry density and bentonite content should be investigated to meet the design specifications (Komine, 2004). Such mixtures are also attracting greater

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Figure 1. Location of bentonite and pumice facilities: a) Bentonite b) Pumice.

attention as clay liners for industrial waste disposal facilities (Komine, 2008). Therefore, several researchers investigated the hydraulic conductivity of bentonite amended clay liners to be used for industrial waste disposal facilities (Daniel, 1984; Chapius, 1990; Pusch, 2001; Chapius et al., 2006; Komine, 2010).

Properly compacted bentonite-sand mixtures are also used as an attractive low-cost liner for lagoons of constructed wetlands. Constructed wetlands are built to provide a natural treatment system for wastewater treatment in small-medium size communities. They usually require a low permeability liner under the wetland basin to prevent the contamination of groundwater or to prevent groundwater from infiltrating into the wetland (Kadlec et al., 2000). Mostly clays, bentonite-aggregate mixtures, and some synthetic materials such as polyvinylchloride (PVC) and high-density polyethylene are used as liner material. As synthetic liners are usually more expensive and more prone to damage than clay-based liners (Kadlec and Knight, 1996), they are generally preferred only at sites where natural clays are not sufficiently available.

The use of pumice as an adsorbent to remove heavy metals from wastewater is a well established process. Pumice is a light, porous igneous volcanic rock. It has a porous structure and a large surface area with open channels that allow water and ions to travel into and out of the crystal structure. Pumice has a skeleton that allows ions and molecules to reside and move within the overall framework. It includes several macro- and micro-scale pores formed by the sudden release of gases during formation (Anonymous, 2010). General composition of pumice contains 60 to 75% SiO_2 , 13 to 17% Al_2O_3 , 1 to 3% Fe_2O_3 , 1 to 2% CaO, 8% Na_2O - K_2O and very low TiO_2 and SO_3 (Özkan and Twicer, 2001). Turkey has enormous pumice reserves especially in the vicinity of extinct volcanoes, such as Erciyes in Kayseri, which is commercially used by local enterprises, for example, to make lightweight concrete or insulative low-density breeze blocks.

Since pumice has a high heavy metal and phosphorus adsorption capacity, it is now being used as substrate material in constructed wetlands for domestic wastewater treatment (Catalfamo et al., 2006; Yavuz et al., 2008; Brooks et al., 2000). Despite these absorbance characteristics, there are limited studies on geotechnical characteristics of pumice (Esposito and Guadagno, 1998; Pender et al., 2006).

In this study, the permeability characteristics of pumice-bentonite mixtures were determined and compared with sand-bentonite mixtures; impacts of grain size and bentonite contents on permeability were evaluated and empirical relationships were derived between the permeability and other geotechnical characteristics determined in Gökalp et al. (2011).

MATERIALS AND METHODS

In this study, permeability characteristics of pumice and sand-based mixture were determined and partial results of previously performed study of Gökalp et al. (2011) were used to evaluate the relationships between the permeability characteristics determined here in this study and the other geotechnical characteristics found at previous study of the authors.

Pumice, sand and bentonite to be used in this study were supplied from commercial facilities. The pumice samples were supplied by a commercial pumice manufacture and trade company in Develi, Kayseri (Figure 1). The sand samples were supplied from a commercial supplier. It is washed and pre-sieved river sand commonly used for construction and contains no soil particles present. The specific gravity of the sand was determined as 2.67. Bentonite was supplied from a commercial bentonite facility located in Çankiri Province of Turkey (Figure 1) and the product is powdered Na-bentonite with at least 78% montmorillonite. Some physical and chemical properties of pumice and powdered bentonite are given in Table 1 (Garden, 2010; Canbensan, 2010).

In order to investigate the effect of grain size on permeability characteristics of the mixtures, sand and pumice samples were both

Table 1. Physical and chemical properties of powdered bentonite and pumice.

Pumice		Bentonite	
Parameter	**Value**	**Parameter**	**Value**
SiO_2 (%)	53.50	Density (g/cm^3)	0.9
Al_2O_3 (%)	10.75	Water Content (%)	9.50
CaO (%)	3.78	pH	9.5
Fe_2O_3 (%)	3.22	Liquid Limit (%)	630
K_2O (%)	3.15	Compactibility (%)	40
MgO (%)	1.95	Wet Strength (N/cm^2)	24.5
Na_2O (%)	1.60	Dry Strength (N/cm^2)	42
pH	6.5	Shear Strength (N/cm^2)	6.25
Lime (%)	6.6	Amount retained over 150 μm (%)	1.20
Moisture Content (%)	10.9	Cation Exchange Capacity (meq/100g)	80-90
Water Holding Capacity (weight-based)	90.2	Specific Gravity	2.75
Total N	0.028	SiO_2 (%)	62.1
Soluble P (ppm)	0.004	Al_2O_3 (%)	15.21
Soluble K (ppm)	4.79	Fe_2O_3 (%)	6.58
Soluble Ca (ppm)	14.019	MgO (%)	2.28
Soluble Mg (ppm)	1.077	Na_2O (%)	1.59
		CaO (%)	1.19
		K_2O (%)	1.13

divided into three different size fractions by dry sieving. The three fractions separated were 2.00 to 1.00 mm, 1.00 to 0.50 mm and 0.50 to 0.25 mm, which were homogeneously mixed with varying contents of bentonite as of 15, 20, 25 and 30% by volume.

Since the permeability characteristics of compacted mixtures are to be investigated, standard Proctor compaction tests were carried out to determine the maximum dry unit weights and optimum moisture contents of mixtures. Compaction tests were carried out in accordance with ASTM D698 (ASTM, 2000a). Standard constant volume swell tests were performed on statically compacted samples of the prepared mixtures to drive relationships between swell potential and permeability characteristics of mixtures. Mixtures were compacted at optimum water content and maximum dry unit weight as specified in the standard Proctor test procedure. One-dimensional oedometer test samples were taken from compacted specimens into a standard 50 mm diameter and 20 mm high consolidation rings. Then the swell tests were carried out in accordance with ASTM D4546 standard test procedure (ASTM, 2000b).

Falling head permeameter was used to determine the hydraulic conductivity of mixtures. Tests were carried out in accordance with ASTM D5084 standard test procedure (ASTM, 2000c) and principles specified at Liu and Evett (1997). Since the mixtures are to be used in compacted state, samples were initially compacted at optimum water content to reach maximum dry unit weights; threafter hydraulic conductivity tests were run on compacted remolded samples.

Since permeability tests for fine material take long time compared to compaction and swelling tests, attempts were made to establish relationships that estimate permeability values from easily and quickly performed test results. Simple regression analysis were performed by using the compaction, swelling and permeability test data to derive equations indicating the relationship between permeability and the other easy-to-determine characteristics. Linear, logarithmic, exponential, and power curve fitting approximations were tried and the best approximation equation with the highest correlation coefficient (R^2) and the least mean absolute error (MAE) was determined for each regression by the following equation, where k_{ai} and k_{pi} represents the actual and predicted permeability, respectively.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|k_{ai} - k_{pi}\right|$$

RESULTS AND DISCUSSION

Experimental results for compaction, swelling and permeability characteristics of pumice and sand-based mixtures with various grain size ranges (2.00 to 1.00, 1.00 to 0.50, 0.50 to 0.25 mm) and bentonite contents (15, 20, 25 and 30%) were presented respectively in Tables 2 and 3.

However, experimental results showed that hydraulic conductivity was between 4.33×10^{-5} – 2.04×10^{-10} m/s for pumice-bentonite mixtures and between 5.89×10^{-5} to 1.94×10^{-10} m/s for sand-bentonite mixtures. Results indicate in general that pumice-based mixtures had slightly lower permeability than sand based mixtures. Komine (2004) observed hydraulic conductivity of sand-bentonite mixture backfill as between 2.66×10^{-10} and4.85×10^{-12} m/s for bentonite contents of 5 to 20% and between 6.87×10^{-12} and 1.21×10^{-12} m/s for bentonite contents of 30 to 50%. The researcher used sand particle diameters of 0.590 to 0.053 mm, therefore obtained smaller hydraulic conductivities than found in current study.

While decrease in permeability was continuous in

Table 2. Geotechnical characteristics of pumice-bentonite mixtures.

Grain Size (mm)	Pumice			
	Bentonite content (%)			
	15	20	25	30
	Dry unit weight (t/m^3)			
2.00 – 1.00	1.292	1.308	1.350	1.375
1.00 – 0.50	1.405	1.425	1.455	1.491
0.50 – 0.25	1.435	1.472	1.509	1.529
	Moisture content (%)			
2.00 – 1.00	26.10	22.50	20.30	20.00
1.00 – 0.50	22.70	19.30	19.00	17.90
0.50 – 0.25	22.20	19.00	18.50	17.30
	Swell potential (%)			
2.00 – 1.00	0.200	1.200	3.165	13.985
1.00 – 0.50	0.225	1.190	2.925	11.105
0.50 – 0.25	0.345	0.940	2.255	9.755
	Permeability (m/s)			
2.00 – 1.00	4.33×10^{-5}	5.00×10^{-6}	2.81×10^{-6}	1.01×10^{-9}
1.00 – 0.50	3.13×10^{-6}	1.56×10^{-6}	1.14×10^{-8}	9.28×10^{-10}
0.50 – 0.25	9.01×10^{-8}	1.24×10^{-8}	1.71×10^{-10}	2.04×10^{-10}

Maximum dry unit weight, optimum moisture content and swell potential were taken from Gökalp et al. (2011).

Table 3. Geotechnical characteristics of sand-bentonite mixtures.

Grain Size (mm)	Sand			
	Bentonite content (%)			
	15	20	25	30
	Dry Unit Weight (t/m^3)			
2.00 – 1.00	1.753	1.768	1.780	1.791
1.00 – 0.50	1.735	1.755	1.760	1.770
0.50 – 0.25	1.717	1.731	1.739	1.757
	Moisture content (%)			
2.00 – 1.00	15.10	15.80	14.40	13.00
1.00 – 0.50	15.50	16.00	15.20	13.80
0.50 – 0.25	15.80	16.30	15.80	14.20
	Swell potential (%)			
2.00 – 1.00	0.215	0.550	1.420	7.585
1.00 – 0.50	0.270	0.410	1.615	8.090
0.50 – 0.25	0.100	0.550	1.700	11.680
	Permeability (m/s)			
2.00 – 1.00	5.89×10^{-5}	1.67×10^{-5}	8.13×10^{-6}	1.36×10^{-9}
1.00 – 0.50	1.62×10^{-6}	9.64×10^{-7}	3.13×10^{-7}	4.97×10^{-10}
0.50 – 0.25	5.69×10^{-8}	3.69×10^{-8}	3.37×10^{-10}	1.94×10^{-10}

Maximum dry unit weight, optimum moisture content and swell potential were taken from Gökalp et al. (2011).

Table 4. MAE and R^2 values for exponential and power curve fitting regressions between bentonite content and permeability.

Bentonite content - Permeability				
Pumice (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	1.95×10^{-5}	2.28×10^{-5}	0.8113	0.7434
1.00 – 0.50	1.23×10^{-6}	1.62×10^{-6}	**0.9340**	0.8940
0.50 – 0.25	6.69×10^{-9}	4.14×10^{-9}	0.8803	0.9042
Total	**2.07×10^{-6}**	2.44×10^{-5}		
Sand (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	5.08×10^{-5}	3.64×10^{-5}	0.7544	0.6748
1.00 – 0.50	1.19×10^{-6}	1.34×10^{-6}	0.7651	0.6811
0.50 – 0.25	1.47×10^{-8}	2.07×10^{-8}	0.8700	**0.8518**
Total	5.20×10^{-5}	**3.77×10^{-6}**		

coarser grain mixtures of both pumice and sand (2.00 to 1.00 and 1.00 to 0.50 mm), reduction of hydraulic conductivity was less, almost ceased, in materials containing more than 25% bentonite and with grain size less than 0.50 mm because voids are almost entirely filled by swollen bentonite. Akgün (2010) investigated the hydraulic conductivity values of sand-bentonite mixtures with bentonite contents of 15 to 30% and sand grain size of 1.18 to 0.075 mm and observed the hydraulic conductivities between 6.4×10^{-9} and 8.9×10^{-12} m/s. The lower hydraulic conductivities than the ones in current study were due to grain size of sand used in that study since 75.1% of sand grains were lower than 0.30 mm in size.

Since linear and logarithmic curve fitting approximations yielded negative permeability for higher bentonite contents, only the power and exponential curve fitting approximations were compared by taking MAE into consideration for pumice and sand-based mixtures. While power curve fitting was yielding lower MAE in some relationships, exponential curve fitting yielded lower MAE values in others. For bentonite content-permeability relationship, power curve fitting yielded lower MAE in sand-based mixtures and exponential curve fitting yielded lower MAE values in pumice-based mixtures (Table 4). The relationships between bentonite content and hydraulic conductivity were presented in Figure 2 for pumice and sand-based mixtures. While the highest R^2 was obtained for grain size range of 0.50 to 0.25 mm for sand based mixtures in power curve fitting, the highest value was obtained for 1.00 to 0.50 mm size range of pumice-based mixtures in exponential curve fitting.

The relationship between dry unit weight and permeability was investigated similar to bentonite content-permeability relationship. While exponential curve fitting was better with respect to MAE for pumice-based mixtures, power curve fitting yielded lower MAE for sand-based mixtures (Table 5). Results revealed lower permeability with increasing dry densities since higher dry densities yielded lower porosities for flow of fluid (Figure 3). Similar findings were also presented by Komine (2004) and Akgün (2010). Again, the highest R^2 values were obtained for the same size groups of pumice and sand-based mixtures as it was in bentonite content-permeability relationship.

The relationship between moisture content and permeability was approximated with power curve fitting for both pumice and sand-based mixtures since power curve fitting yielded lower MAE values for both mixtures than exponential curve fitting (Table 6). Increasing moisture contents revealed increasing permeability (Figure 4). While the highest R^2 was obtained for grain size range of 1.00 to 0.50 mm for sand-based mixtures in power curve fitting, the highest value was obtained for 0.50 to 0.25 mm size range of pumice-based mixtures.

The relationship between swell potential and permeability was investigated with exponential curve fitting for both pumice and sand-based mixtures since exponential curve fitting yielded lower MAE values for both mixtures than power curve fittings (Table 7). Decreasing permeability was observed with increasing swell potential (Figure 5). The highest R^2 was observed for grain size range of 1.00 to 0.50 mm for sand-based mixtures in exponential curve fitting and the highest value was obtained for 2.00 to 1.00 mm size range of pumice-based mixtures. Shirazi et al. (2010) indicated that swelling characteristics of sand-bentonite mixtures followed exponential trend line. Mishra et al. (2011) observed decreasing permeability with increasing free swell and used exponential curve fitting to present the relationship between permeability and free swell.

Regression equations for permeability estimation by using different variables were summarized in Table 8 for pumice-based mixtures and in Table 9 for sand-based mixtures. Overall evaluation of regression equations with regard to MAE and R^2 values showed that while dry unit weight yielded the least MAE and the highest R^2 values for pumice-based mixtures, swelling potential yielded the best estimations for sand-based mixtures.

Regulations require a hydraulic conductivity of lower

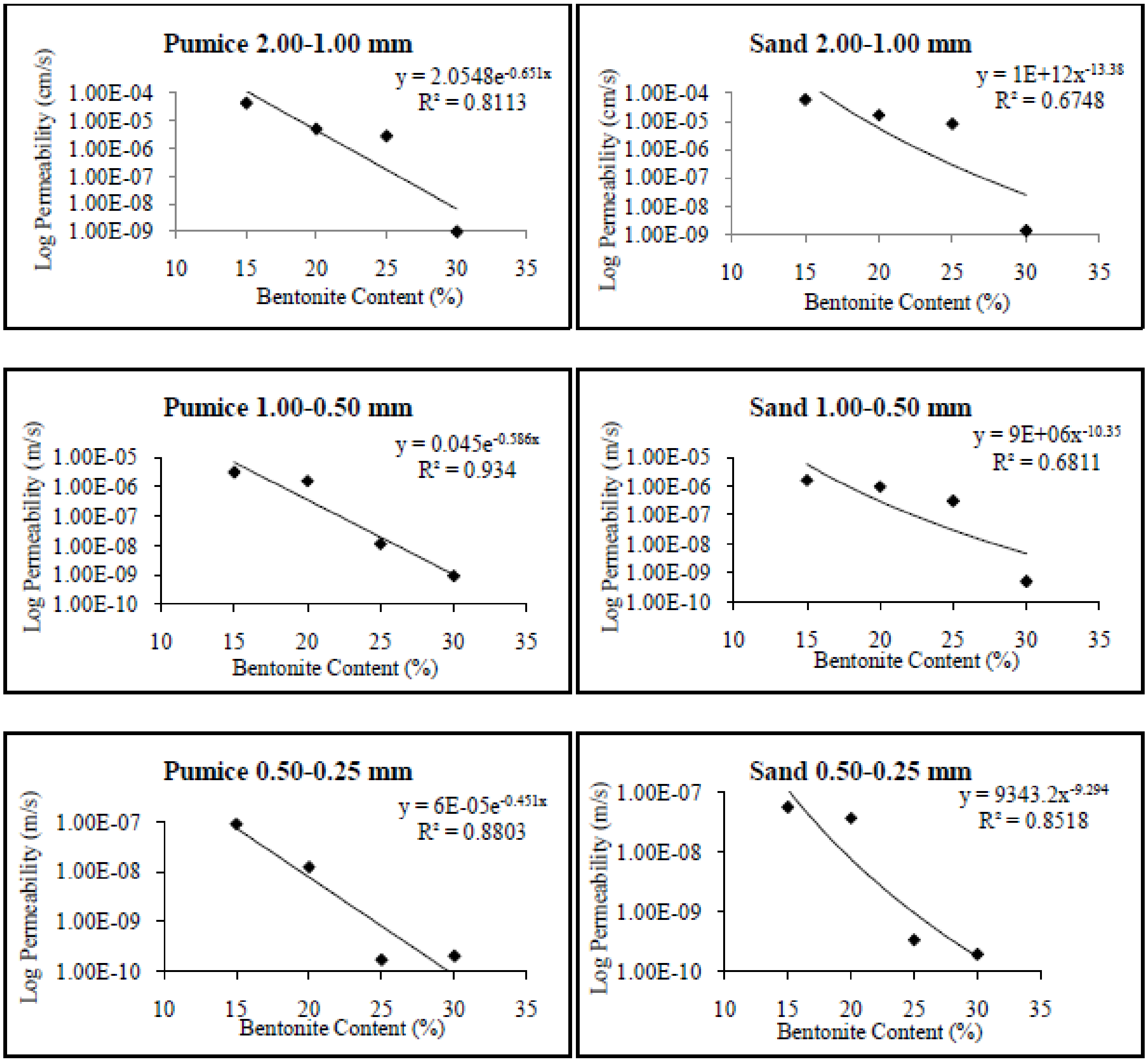

Figure 2. Bentonite content – permeability relationships.

than 1×10^{-9} m/s for compacted clayey material to be used in liners of waste repository sites and constructed wetland lagoons (USEPA, 1993). While both pumice and sand-based mixtures with bentonite contents lower than 30% and all grain sizes (except 25% and 0-50 to 025 mm) were able to meet this criteria with regard to hydraulic conductivity, only the bentonite content of 30% for all grain sizes and 25% for 0.50 to 0.25 mm were considered suitable for such sites.

Conclusions

In this research that investigates the permeability characteristics of pumice-bentonite and sand-bentonite mixtures and attempt to estimate permeability of mixtures from the other geotechnical characteristics, the following conclusions can be drawn:

1) Pumice-based mixtures were able to provide almost identical permeability values with sand-based mixtures. Therefore, locally abundant material, pumice may be used as an alternative to sand in mixtures to be used for liners of waste repository sites and constructed wetland lagoons.
2) Exponential and power curve fitting regressions were found to be suitable for permeability estimation from easily-determined characteristics.
3) While dry unit weight yielded the best estimations for pumice-based mixtures, swell potential yielded the best results for sand-based mixtures.
4) According to relevant regulations for liners of waste

Table 5. MAE and R^2 values for exponential and power curve fitting regressions between dry unit weight and permeability.

Dry unit weight - Permeability				
Pumice (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	1.60×10^{-6}	6.61×10^{-6}	0.7697	0.7650
1.00 – 0.50	5.61×10^{-7}	5.28×10^{-7}	**0.9574**	0.9578
0.50 – 0.25	4.87×10^{-9}	2.09×10^{-8}	0.9389	0.9394
Total	**2.17×10^{-6}**	7.16×10^{-6}		
Sand (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	5.90×10^{-5}	4.98×10^{-5}	0.7033	0.7008
1.00 – 0.50	1.39×10^{-6}	1.07×10^{-6}	0.6127	0.6097
0.50 – 0.25	8.75×10^{-9}	9.44×10^{-9}	0.7736	**0.7741**
Total	6.04×10^{-5}	**5.09×10^{-6}**		

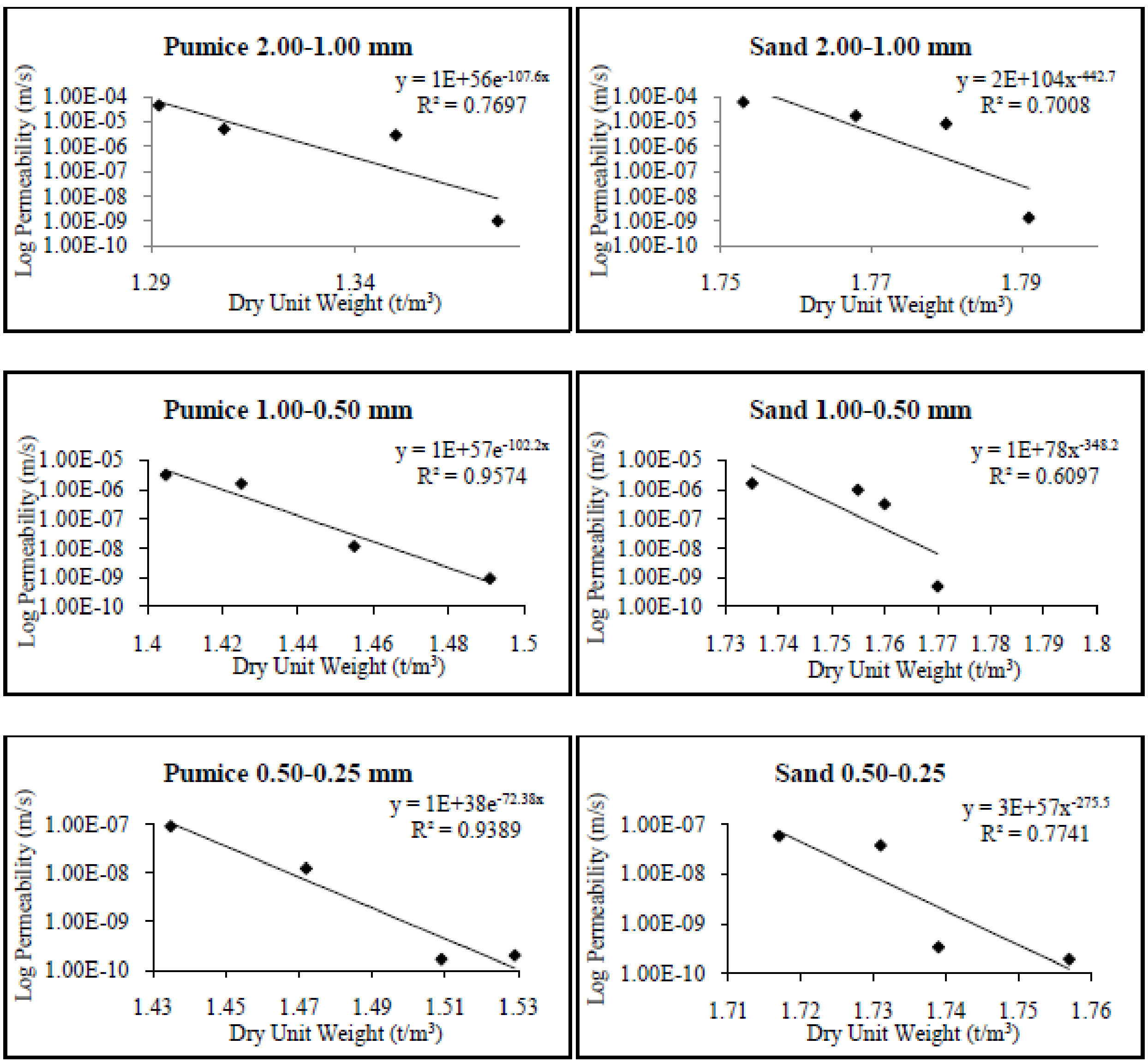

Figure 3. Dry unit weight – permeability relationships.

Table 6. MAE and R^2 values for exponential and power curve fitting regressions between moisture content and permeability.

Moisture content - Permeability				
Pumice (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	1.77x10^{-5}	1.53x10^{-5}	0.5194	0.5343
1.00 – 0.50	8.02x10^{-7}	1.36x10^{-6}	0.6222	0.6436
0.50 – 0.25	5.88x10^{-9}	1.29x10^{-8}	0.7682	**0.7738**
Total	1.85x10^{-6}	**1.67x10^{-5}**		
Sand (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	5.81x10^{-5}	4.51x10^{-5}	0.8003	0.8226
1.00 – 0.50	7.64x10^{-7}	9.51x10^{-6}	0.9152	**0.9248**
0.50 – 0.25	1.81x10^{-8}	1.96x10^{-9}	0.4912	0.4877
Total	5.89x10^{-5}	**4.61x10^{-6}**		

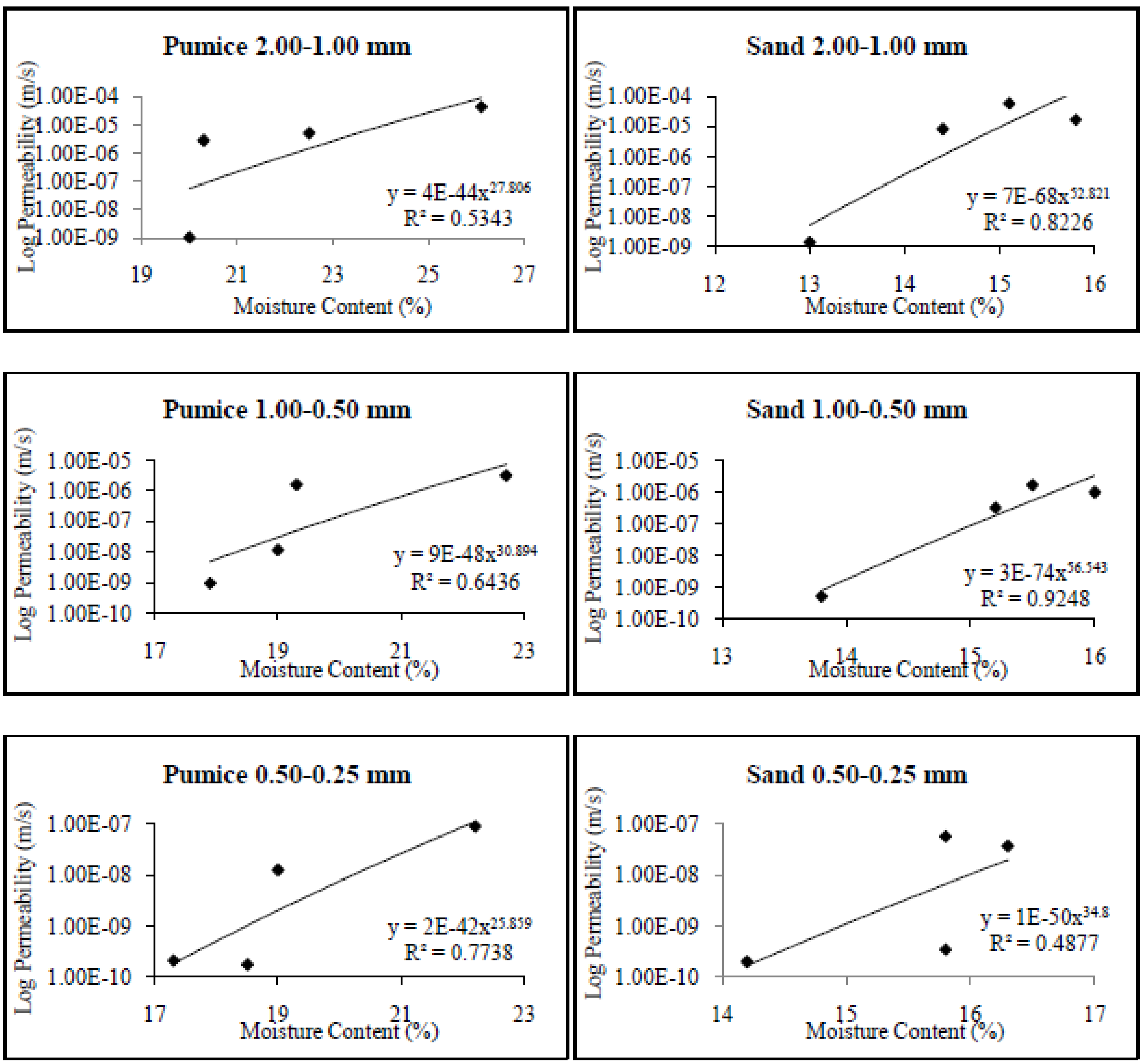

Figure 4. Moisture content – permeability relationships.

Table 7. MAE and R^2 values for exponential and power curve fitting regressions between swell potential and permeability.

Swell potential - Permeability				
Pumice (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	$6.25x10^{-5}$	$3.53x10^{-5}$	**0.9842**	0.8130
1.00 – 0.50	$8.81x10^{-7}$	$1.64x10^{-6}$	0.7904	0.8683
0.50 – 0.25	$2.28x10^{-8}$	$9.90x10^{-9}$	0.4668	0.8006
Total	**$7.16x10^{-6}$**	$3.70x10^{-5}$		
Sand (mm)	**MAE (Exponential)**	**MAE (Power)**	**R^2 (Exponential)**	**R^2 (Power)**
2.00 – 1.00	$6.42x10^{-6}$	$3.79x10^{-5}$	0.9955	0.8721
1.00 – 0.50	$1.33x10^{-7}$	$8.25x10^{-7}$	**0.9982**	0.8902
0.50 – 0.25	$2.02x10^{-8}$	$1.56x10^{-8}$	0.5245	0.8045
Total	**$6.57x10^{-6}$**	$3.87x10^{-5}$		

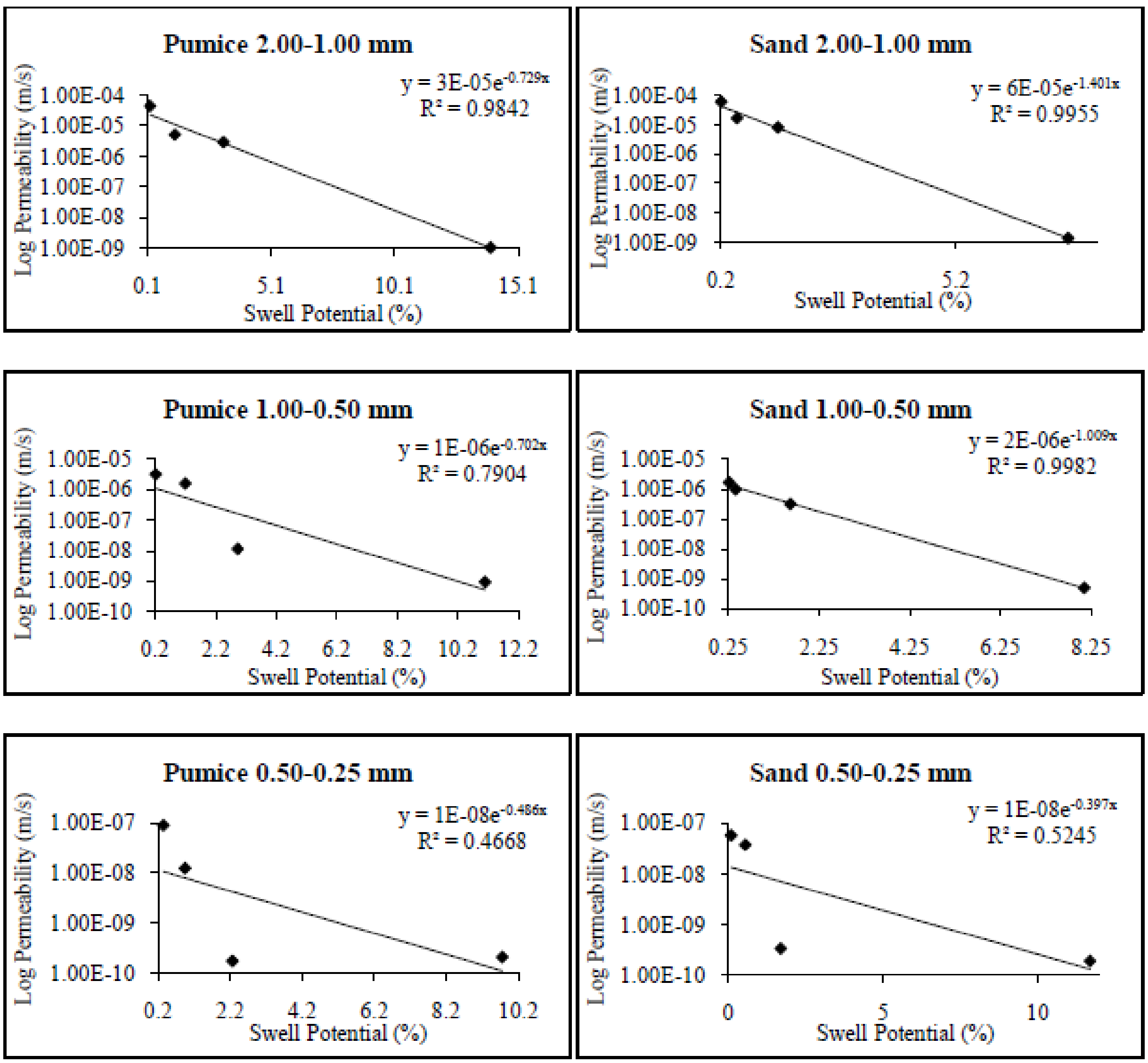

Figure 5. Swell potential – permeability relationships.

Table 8. Regression equations for pumice-based mixtures.

Variable	Size range (mm)	Permeability estimation equations (Pumice - Bentonite mixtures)	
Bentonite content BC (%)	2.00 – 1.00	$k = 2.0548\ e^{-0.651\ (BC)}$	$R^2 = 0.8113$
	1.00 – 0.50	$k = 0.045\ e^{-0.586\ (BC)}$	$R^2 = 0.9340$
	0.50 – 0.25	$k = 6x10^{-5}\ e^{-0.451\ (BC)}$	$R^2 = 0.8803$
Dry unit weight γ_d (t/m^3)	2.00 – 1.00	$k = 1x10^{56}\ e^{-107.6\ (\gamma_d)}$	$R^2 = 0.7697$
	1.00 – 0.50	$k = 1x10^{57}\ e^{-102.2\ (\gamma_d)}$	**$R^2 = 0.9574$**
	0.50 – 0.25	$k = 1x10^{38}\ e^{-72.38\ (\gamma_d)}$	$R^2 = 0.9389$
Moisture content w (%)	2.00 – 1.00	$k = 4x10^{-44}\ w^{27.806}$	$R^2 = 0.5343$
	1.00 – 0.50	$k = 9x10^{-48}\ w^{30.894}$	$R^2 = 0.6436$
	0.50 – 0.25	$k = 2x10^{-42}\ w^{25.859}$	$R^2 = 0.7738$
Swell potential SP (%)	2.00 – 1.00	$k = 3x10^{-3}\ e^{-0.729\ (SP)}$	$R^2 = 0.9842$
	1.00 – 0.50	$k = 1x10^{-6}\ e^{-0.702\ (SP)}$	$R^2 = 0.7904$
	0.50 – 0.25	$k = 1x10^{-8}\ e^{-0.486\ (SP)}$	$R^2 = 0.4668$

Table 9. Regression equations for sand-based mixtures.

Variable	Size Range (mm)	Permeability estimation equations (Sand - Bentonite mixtures)	
Bentonite content BC (%)	2.00 – 1.00	$k = 1x10^{12}\ (BC)^{-13.38}$	$R^2 = 0.6748$
	1.00 – 0.50	$k = 9x10^{6}\ (BC)^{-10.35}$	$R^2 = 0.6811$
	0.50 – 0.25	$k = 9343.2\ (BC)^{-9.294}$	$R^2 = 0.8518$
Dry unit weight γ_d (t/m^3)	2.00 – 1.00	$k = 2x10^{104}\ (\gamma_d)^{-442.7}$	$R^2 = 0.7008$
	1.00 – 0.50	$k = 1x10^{78}\ (\gamma_d)^{-348.2}$	$R^2 = 0.6097$
	0.50 – 0.25	$k = 3x10^{57}\ (\gamma_d)^{275.5}$	$R^2 = 0.7741$
Moisture content w (%)	2.00 – 1.00	$k = 7x10^{-68}\ w^{52.821}$	$R^2 = 0.8226$
	1.00 – 0.50	$k = 3x10^{-74}\ w^{56.543}$	$R^2 = 0.9248$
	0.50 – 0.25	$k = 1x10^{-50}\ w^{34.8}$	$R^2 = 0.4877$
Swell potential SP (%)	2.00 – 1.00	$k = 6x10^{-5}\ e^{-1.401\ (SP)}$	$R^2 = 0.9955$
	1.00 – 0.50	$k = 2x10^{-6}\ e^{-1.009\ (SP)}$	$R^2 = 0.9982$
	0.50 – 0.25	$k = 1x10^{-8}\ e^{-0.397\ (SP)}$	$R^2 = 0.5245$

repository sites and constructed wetland lagoons, bentonite content of ≥ 30% is recommended for both pumice and sand-based mixtures with grain between 2.00 and 0.50 mm and ≥25% for mixtures with grain sizes less than 0.50 mm.

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